# STRATEGIES FOR RELIABLE ARC FLASH DETECTION IN LOW-VOLTAGE SWITCHGEAR


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***Abstract*** - Reliably detecting the ignition of an arc flash inside low-voltage metal enclosed switchgear using an arc flash detection system presents a number of technical challenges and requires careful system design to provide maximum equipment and personnel protection. The proper placement of sensors throughout the switchgear is critical to ensuring reliable arc flash detection. Given the large number of potential switchgear design variations, the best way to ensure reliable arc flash detection is through verification of sensor placement by creating true arcing events at a high power test lab using worst-case switchgear configurations in which the detection system will be applied. This paper will briefly discuss the tradeoffs between fiber optic and wired point sensors and will provide extensive treatment of methods to determine sensor placement, sensitivity and quantity within a given low-voltage switchgear design as well as strategies to avoid nuisance operation of the arc flash detection system.

*Index Terms* – Arc flash detection, arc flash testing, arc sensor placement, low-voltage switchgear, arc energy reduction

## I. INTRODUCTION

Arc flash detection (AFD) systems have been applied in electrical equipment for over two decades [1]. Recently in the United States there has been increasing interest in utilizing AFD systems in low-voltage metal enclosed switchgear [2][3]. This increased interest in AFD systems is driven, at least in part, by the inclusion of the “energy-reducing active arc flash mitigation system” method as defined in Article 240.87 of the 2014 edition of the National Electrical Code [4].

Since arc flash detection systems are increasingly being relied upon to protect personnel by reducing the incident energy [5], this in turn will affect the arc flash labeling on the electrical equipment. As a result of lowering the incident energy (as reflected on the arc flash label), certain users may modify their personal protective equipment (PPE) requirements and reduce arc flash boundaries. This presents something of a double-edged sword – not only does an AFD system imply that the equipment is safer, which may cause users to wear less PPE (which, in turn, reduces their level of protection should there be an *unmitigated* arc flash), but it may also drive some users to modify their energized work practices. As a result, it is extremely critical that the AFD system functions predictably and reliably, especially when it is used to reduce the risk to personnel.

The reliability requirement of an arc flash detection system is twofold: it must always operate when an arc flash occurs inside the protected equipment and it must never operate if an arc flash is not present. In other words, the system must not be prone to nuisance operation. Clearly, non-operation of the system during an arc event presents a larger threat to safety, but a nuisance operation can result in critical processes being taken offline unnecessarily. As a result, the AFD system must be carefully designed to avoid both.

There are a number of factors that must be considered when designing a reliable arc flash detection system. From the standpoint of avoiding false negatives, these factors include: 1) the type of sensors used to detect the ignition of an arc flash, 2) the placement of the sensors throughout the equipment so that the light from an arc flash will be detected regardless of where the arc flash originates and 3) techniques for system monitoring to detect problems with the AFD system that could prevent proper functioning.

From the standpoint of avoiding nuisance operation, the system must have security features that validate the presence of a true arcing fault before sending a trip signal. However, careful consideration is necessary to weigh the security features employed and how they could negatively affect the response time of the AFD system.

## II. ARC FLASH SENSOR TYPES

The vast majority of AFD systems use a light signal to detect the ignition of an arc flash (and a secondary signal for security, such as overcurrent). Many of these systems utilize fiber optic sensors to detect and transmit the light signal. There are two main types of fiber optic sensors: Fiber optic point sensors and fiber optic loop sensors. Fiber optic point sensors tend to be employed in enclosed cubicles, such as breaker compartments, while fiber loops may be installed to provide coverage over broad, open areas, such as bus compartments [6].

Fiber point and loop sensors benefit from their simplicity. All of the electronic elements associated with arc flash detection reside within the arc flash detection relay. Testing the integrity of the fiber can be accomplished automatically via the relay by sending a pulse of light in one end of the fiber and measuring its return through the other end of the fiber loop [6]. However, there are a number of other factors that must be considered with fiber optic loop and point sensors.

First and foremost, fiber optic cables cannot be spliced together as easily or reliably as copper wires. This has implications for large lineups of new electrical equipment that may be comprised of multiple shipping splits, or sections. This drawback is typically addressed in one of two ways: either each shipping split will contain a complete AFD system including the relay, or the fiber optic sensors will be installed in the field after the equipment has been set in place. Neither of these solutions is ideal. The first may drive up the cost of the system by requiring additional relays and the second results in an AFD system that leaves the factory incomplete, untested and oftentimes relying on a third party to install the fiber sensors. Field installation of the sensors may lead to variations in sensor placement and other deviations from factory guidelines. It also may be challenging or impossible to reach certain areas of a fully assembled and installed switchgear assembly to install the sensors, leaving some zones unprotected.

Fiber optic cables also have other shortcomings. A light signal traveling through a typical fiber optic cable attenuates faster than an electrical signal traveling through a typical copper cable. As a result, fiber optic runs have limits on length measured in the tens of meters [6] versus hundreds of meters for copper [7]. For longer equipment assemblies, this could result in the need for more relays, thereby driving up costs. Fiber optic cables also have larger bend radii requirements [7] than copper, which could increase field installation risk if the installer is not familiar with the bend radius limits or if the fiber is modified later during maintenance activities.

Finally, fiber optic loop cables are delicate and difficult to see once installed in electrical equipment. Both of these factors can result in unintended damage to the fiber optic cable during equipment maintenance activities. Knicks, cuts, improper bends, or exposure to high heat can all result in damage to fiber optic cables and possibly affect the proper functioning of the AFD system.

An alternative method for detecting the light from an arc flash is via non-fiber optic point sensors containing photocells that are wired back to the arc detection relay. Since the wires for these point sensors can be included in the standard wiring harness of the electrical equipment, it is easy to distribute wired point sensors across various shipping splits during the manufacturing process of the new equipment and reconnect them to the main arc detection relay during field commissioning. This permits the sensors to be installed in the factory and the system to be completely tested before it ships. This not only proves that the system functions before it leaves the factory but it also enables stricter control of sensor placement. Sensors can also be easily installed in otherwise difficult-to-reach locations within the equipment before it is completely assembled.

Arc flash detection systems that use wired point sensors are also capable of performing self-supervision to detect sensor failures or loss of sensor connectivity [8]. Furthermore, wired point sensors that can be connected in series enable more sensors to be connected to each sensor channel on the relay, thereby reducing the overall number of relays necessary for lineups with large numbers of point sensors.

Wired point sensors are also mechanically robust. While performing arc testing with the AFD system, each point sensor was able to withstand seventeen arc fault tests limited to 2 cycles or less without having to be replaced. Furthermore, while performing arc-resistant testing per C37.20.7 [9] on a current-limiting arc quenching device [10], the point sensor located above the finger clusters of the circuit breaker where the arc was initiated survived numerous tests. Granted, the arcing duration of each test was limited to 4 ms or less due to the high-speed operation of the arc quenching device, there was still substantial heat and light generated in the compartment, millimeters from the sensor, as the arc wire vaporized.

Finally, point sensors (fiber optic or wired) can enable the end user to more accurately pinpoint the location of the arcing fault after the event because the relay will annunciate which sensor(s) detected the light from the arc flash event. This feature is particularly useful when the arc flash detection system is used in conjunction with a high-speed, current limiting arc quenching device that operates fast enough to minimize or eliminate damage to the equipment [10]. Without this feature, it can be challenging to determine the cause and location of the arcing fault since the evidence of the fault can be limited.

## III. DETECTING ARCS IN LOW-VOLTAGE SWITCHGEAR – CASE STUDY

As mentioned above, reliable arc flash detection is critical, especially when AFD systems are employed as a means of personnel protection. Because point sensors sense light at a single point, as opposed to a continuous radial field of view as with fiber optic loop sensors, greater care must be taken to determine sensor location for optimum arc light detection. Taking into consideration the variables of AFD system performance and limitations, as well as those of the switchgear construction, one could theoretically determine good locations for the light sensors. However, validating those locations with testing gives proof of proper system design.

In the past, general guidance has been given by AFD system manufacturers as to where sensors should be located. Areas with the highest likelihood of arc flash occurrence are targeted for sensor coverage. The shortcoming with solely giving general guidelines lies in the large variation of power distribution equipment designs. For instance, stating that sensor coverage needs to target the compartment for a draw out low-voltage breaker fails to cover the finer points of that compartment's construction details. What if there are safety shutters, arc chute hoods, or other features that could block arc light transmission to the sensors? In the case of a bus compartment, how dense must the bus be, or how many bus braces does it take to block arc light from the sensors? These questions can only be confidently answered through testing.

In an effort to prove that the AFD's zone of protection covered all areas of the switchgear, testing was performed on a particular model of switchgear with an AFD system installed. The testing that was performed is described in the following sections.

### *A. Light Sensor Performance*

The light sensor used in the testing had an 8k lux sensitivity, and a 360 degree detection radius (Fig. 1).

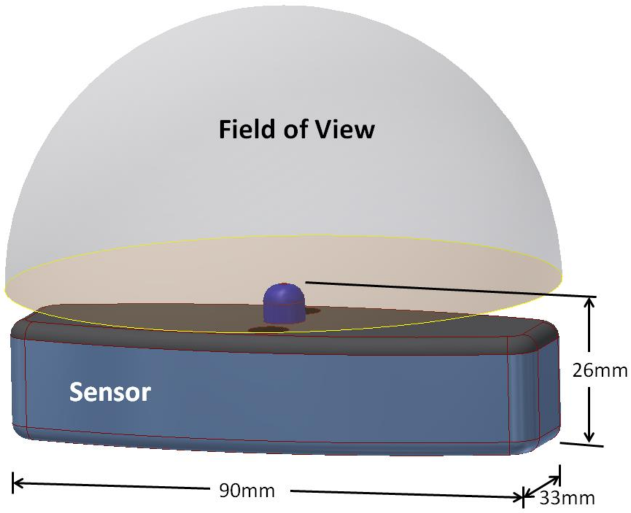


Fig. 1 Sensor with field of view shown

*B. Theoretical Placement of Sensors*

Since safety shutters and arc chute hoods are common in the equipment's circuit breaker compartments, a sensor location was chosen to strategically give it a field of view of the breaker's primary connections in spite of these obstacles (Fig. 2).

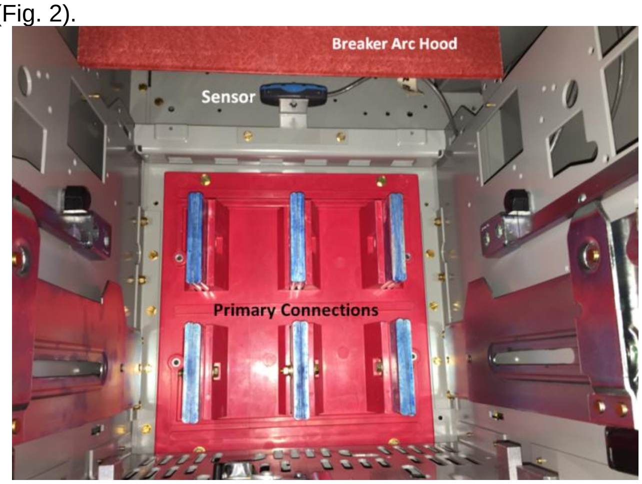


Fig. 2 Breaker compartment (safety shutters not shown)

The bus compartment contained extensive bus, barriers, and bracing, so sensors were placed in a way that appeared to give sensor coverage to all major open spaces in this compartment (Fig. 3). Since light intensity is inversely proportional to the square of the distance from the source, and bus compartments are very tall, sensors were placed at the top and bottom of this compartment to ensure that there would be a sensor close to any arc flash.

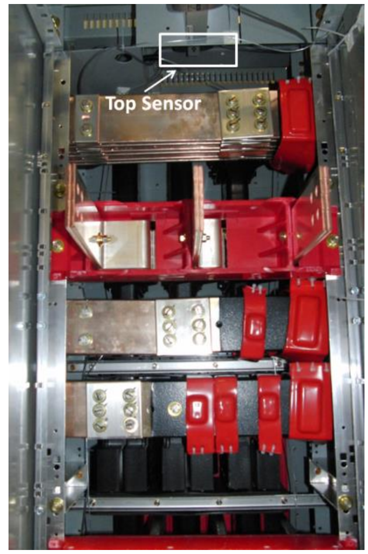


Fig. 3 Bus compartment showing top sensor location

Cable compartment obstructions can vary greatly based upon the number of cables connected to each breaker and presence of current transformers (CTs). Consequently, sensors were also installed in the top and bottom of the cable compartment (Fig. 4).


Fig. 4 Cable compartment (top sensor not visible, location noted)

*C. Switchgear Construction for Sensor Placement Testing*

Given that switchgear is highly configurable, a configuration was chosen that would be absolute worst-case for blocking arc fault light from the sensors. While basic compartment construction is standard for this switchgear model, the contents of those compartments vary greatly. All available compartment barriers were installed – those isolating compartment from compartment. The highest ampacity bus was installed and black bus insulation was applied, including joint booting, with the understanding that the black bus would absorb the arc light rather than allow it to reflect off of the bus (Fig. 5). The equipment was fully loaded with breakers, breaker shutters, breaker load cables (Fig. 4), and relay-class CT's on each breaker's load side bus.

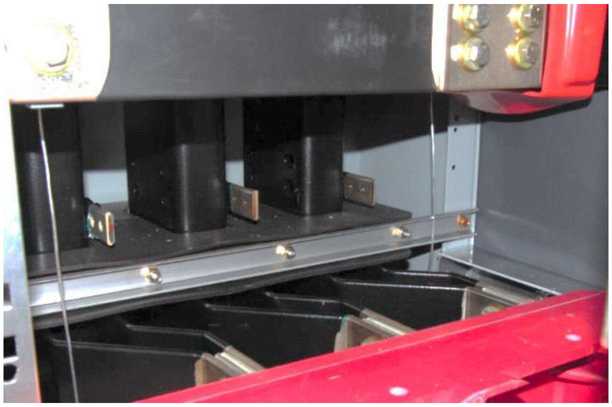

Fig. 5 Black bus insulation

The testing was performed based on the assumption that if all arcs were sensed by the sensors in the planned locations with this equipment configuration, then the sensor locations would work effectively for all other configurations.

*D. Testing With Simulated Arc Fault Light*

Given the expense of subjecting switchgear to true arc faults, an effort was made to create a light source that accurately simulated arc flash light. A lux meter with adequate response time and a peak hold feature was used to take several measurements of open-air arc flashes at 600 V ac and 85 kA. In this test, exposed three-phase bus with a 254 mm [1 inch] air gap between conductors was energized with a shorting wire across the phases for arc flash ignition. Measurements of the arc light intensity at 1830 mm [6 feet] from the source had a mean of 219k lux. A xenon strobe was developed that could be adjusted to match this light lux value at 1830 mm [6 feet] away, and could be placed at various locations in the switchgear for testing (Fig. 6).

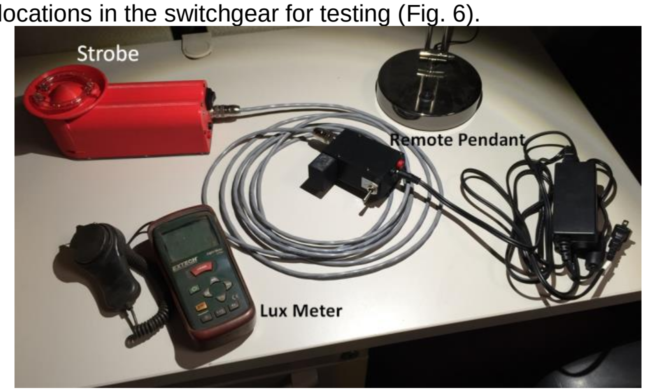


Fig. 6 Xenon strobe and lux meter

Starting in the cable compartment, the xenon strobe was placed in a location that was farthest away from each of the sensors in that compartment and the strobe was operated (Fig. 7). Neither sensor detected the strobe's light. The strobe was then moved to a location in which only the top breaker's cable terminations were between it and the top sensor in that compartment. The sensor successfully detected the light in this test. This manner of testing was replicated for the bus and breaker compartments. The result of testing with the strobe was that unless there was a direct line-of-sight between the strobe and sensor, the sensor would not detect the light.

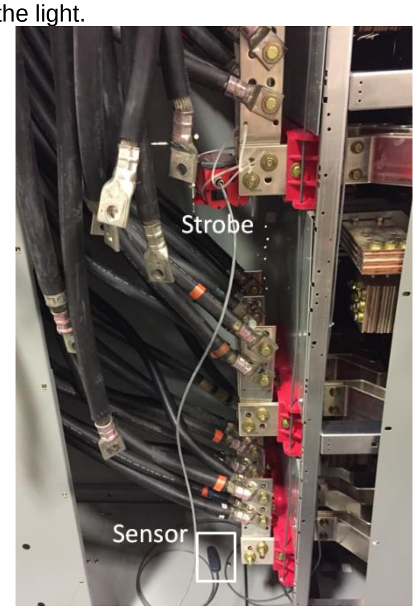


Fig. 7 Strobe in cable compartment

*E. Testing With Arc Faults*

Questions arose around the xenon strobe's ability to accurately simulate arc flash light. Do arc flashes emit more lumens? Arc flashes are dynamic and move around due to magnetic forces. Does this make them easier to detect? The decision was made to take the switchgear to a high power laboratory for arc fault testing to answer these questions.

Short arc faults, averaging 1 cycle in duration, were initiated throughout the equipment in areas farthest away and with the most obstructed views from the light sensors at multiple voltage and current levels. Testing was also performed with different ignition sources with the thought that different sources may produce light at different wavelengths, and thus affect sensor detection. Solid strand shorting wire, scrap bus, tools, and chain were all used as ignition sources. Through this testing, the best sensor locations were determined for the sensors to be able to detect the arc flash light.

The testing proved that the xenon strobe, while having the same lux as an arc flash, was not able to simulate an arc flash and demonstrated that artificial light sources are not adequate for the development of sensor placement rules.

## IV. METHODS TO AVOID NUISANCE TRIPPING FROM AIR CIRCUIT BREAKER OPERATION

As mentioned previously, the most widely used method for detecting arcing events in electrical distribution equipment is to use both current and light sensors. When these two input signals are AND'ed in a protective relay, it greatly reduces the potential for a nuisance trip. It has been proven that using only light input can cause a false trip if a sufficient light source is exposed to the sensor. Furthermore, current-only is not ideally used for the exclusive tripping input, as a fault downstream of the electrical equipment would result in triggering operation.

There are other methods that can be used to detect an arc flash such as pressure sensors and voltage signatures but these methods can add additional undesirable delay to the activation of the system. There could be a reason to choose one of these methods of detection but it would be necessary to take the added time delay into account when calculating the incident energy that personnel may be subjected to in the case of an arcing event.

While current and light sensors are the most common approach for arc flash detection, there are still some drawbacks. In low-voltage equipment, circuit interrupters in air are very common. During a fault downstream of the equipment, an air circuit breaker (ACB) will emit light from the arc chutes when the moving contacts separate and the arc energy is pulled into the arc chute. When this light escapes the ACB, a light sensor placed nearby may receive enough lux to activate. In this scenario, the through-fault current provides the first input and the AFD system cannot discern between the light emitted from the ACB arc chutes and the light emitted from an arcing fault, thus a nuisance operation may occur.

In some industries, a nuisance operation of the arc detection system may not be a significant issue. But in many industries, such as processing plants, thousands of dollars of losses can result from unplanned downtime. For such industries where uptime is critical, it is paramount that a blocking scheme be utilized in the AFD system to prevent nuisance operations for the scenario described above.

Several methods can be used to initiate the blocking sequence:

A. Blocking Timer
B. ACB Protective Relay Input
C. Breaker Auxiliary Contacts
D. Special Purpose Contact
E. Differential Protection Schemes
F. Directional Shielding of Sensors

Note: Light and current are assumed to be the sensory inputs to the AFD system in the following methods.

*A. Blocking Timer*

During an arcing fault event, the signals from the light sensor and current sensor are received by the AFD system at approximately the same time (Fig. 8). However, if a fault occurs downstream of the AFD protected equipment, the current sensor input will go high significantly sooner than the signal from the light sensor which may be activated from the light emitted by the ACB interrupting the downstream fault (Fig. 9). This time differential can be measured during high power testing and can be used by the microprocessor in the AFD system to block the light sensor input for a given time period. This period could be programmable or preset and would be determined by the type of ACB protection device in the system.

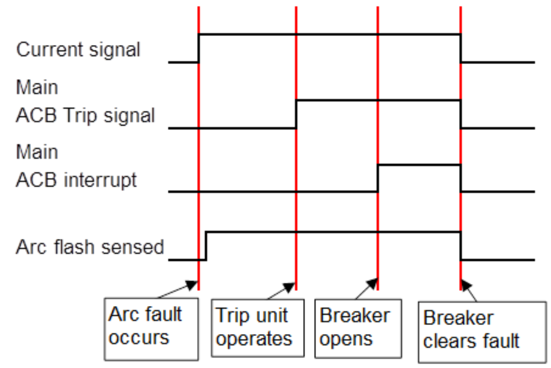


Fig. 8 Timing sequence for uncontrolled arcing event

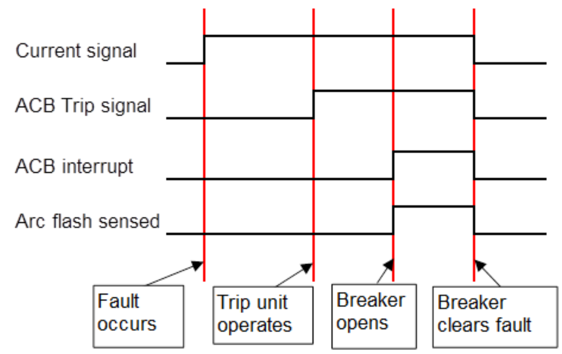


Fig. 9 Timing sequence for ACB interrupting downstream fault

The most significant advantage of this method is the simplicity. Both sensory inputs are already provided to the AFD system, thus no additional sensors or wiring is required. It simply becomes a firmware change to the AFD system. Conversely, the disadvantage is the finite blocking timer. For ACBs that have variable opening times, such as a short-time withstand rating, the variability could be anywhere from approximately 48 ms to 500 ms. With this variability, the blocking timer would have to be set for 500 ms, the worst case scenario. This means the equipment is unprotected from arcing events for 500 ms whenever a breaker operates. However, this solution works very well for overcurrent trip devices with limited withstand capability.

*B. ACB Protective Relay Input*

During a normal overcurrent event, the protective relay or trip unit sends the trip signal to the trip actuator in the circuit breaker which releases the stored energy in the mechanism to mechanically open the moving contacts within the ACB. This same trip signal can be simultaneously sent to the AFD system to initiate a blocking window, effectively telling the AFD system that the circuit breaker is clearing a fault external to the equipment and that the subsequent light should be ignored for a set period of time (Fig. 10).

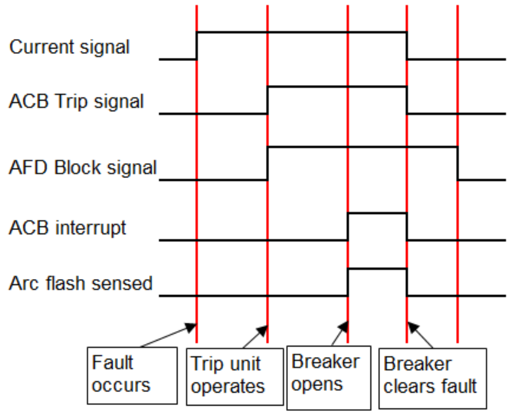


Fig. 10 Timing sequence for trip unit initiating a blocking window

The advantage of this method is, once again, in its relative simplicity. The protective relay can be easily connected to the AFD system to send a signal when it has tripped the ACB, thus initiating a blocking window. The disadvantage is that the protective relay or trip unit are not the only devices that can trip an ACB. These devices include a shunt trip, under-voltage release, and the mechanical trip push button. One scenario that can potentially emit enough light from the arc chutes to activate the light sensor in the breaker cubicle is jogging a large motor using the mechanical trip and close buttons on the circuit breaker.

*C. Breaker Auxiliary Contacts*

Another method is to wire a circuit breaker auxiliary contact to the AFD system so that it can communicate that the ACB is opening. These contacts are normally connected to the trip shaft of an ACB which means at some point during the trip shaft rotation the contacts will change state. The important factor in this method is that the auxiliary contacts change state before the main contacts separate. The time between the two sets of contacts changing state is critical so the AFD system microprocessor has time to initiate the blocking window.

The advantage for this method is the finite blocking window that is initiated right before light leaves the arc chutes and ends right after the light emission stops. The disadvantage for this method is that it is device-specific. This means if the auxiliary contacts in a particular ACB do not change state before the main contacts part, this method is not feasible. This solution must be verified as a system for each unique combination of ACB auxiliary contact and AFD.

*D. Special Purpose Contact*

This method is very similar to the Breaker Auxiliary Contact method, except this contact is specially designed to operate at a specific point during the tripping of the ACB. This ensures that the contact will change state at a given time before the main contacts separate. This method minimizes the blocking window since it more accurately aligns with the parting of the main contacts.

The advantage is a more accurate blocking window. The disadvantage is that this type of contact is not typical and requires a design change to the ACB.

*E. Differential Protection Schemes*

The use of differential protection schemes is very common when trying to discern where in an electrical circuit the current is flowing. By placing one of the current sensors on the incoming conductors and comparing the output of this sensor to the output of a current sensor on the outgoing conductors, one can discern if the current flow is between the sensors or not. A fault outside the equipment would induce the same current in both sensors thus enabling an AND logic gate to block the operation of the AFD.

One advantage of this method is this AFD system can be applied in existing switchgear that already contains differential current sensors. Another advantage is that it doesn't require connections to multiple breakers. The disadvantage of this method is when the electrical equipment doesn't already use this protection scheme and all required current sensors must be added.

*F. Directional Shielding of Sensors*

Some AFD systems rely on the use of barriers to block the light emitted from a breaker clearing a fault from reaching the light sensor. However, such systems must be tested extensively to ensure proper operation and to ensure that the zone around the ACB is adequately protected in the event an unintended arc occurs in the compartment. If none of the aforementioned blocking methods are achievable, it may be necessary to resort to this less preferred method.

Regardless of the blocking method chosen, the integrity of the signal is of the utmost importance. All blocking methods should have continuous monitoring capabilities to detect when the system is not operating correctly. For example, if using a digital input over a hard wired connection, methods should be employed to determine if the connection is broken or intermittent. If using a fiber optic cable, a pulse train can be sent from the transmitter to the receiver which then can detect a broken or disconnected fiber.

## V. CONCLUSIONS

As codes such as NEC section 240.87 drive the adoption of arc flash detection systems in low-voltage equipment to reduce arc energy, the design and implementation of such systems becomes increasingly important. Understanding the types of AFD systems available and their pros and cons is only part of the equation. Proper sensor placement to ensure complete equipment coverage is even more crucial to a properly functioning and effective system. As this case study has shown, sensor placement must be tailored specifically to the type and configuration of equipment being protected. Furthermore, verification of a robust anti-nuisance operation design and ideal sensor placement is best determined through true arc fault testing performed with the equipment to be protected.

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## VII. VITAE

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